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TECHNIQUES AND EXAMPLES FOR ZERO-g MELTING AND SOLIDIFICATION PROCESSES

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ABSTRACT

Many new processes which can exploit the weightless environment of space have been suggested as possibilities for making improved or unique materials. A large number of these will involve, at some stage, a containerless melt or transfer of molten material. Some of the physics and technology problems associated with these processes are discussed. The range of applicability of some new electromagnetic process control methods is also presented.

INTRODUCTION

The prospect of the availability of manned experimental facilities in the nearly weightless environment of near earth orbit opens up a number of exciting possibilities for basic studies in metallurgical and ceramic processing. Even at this point in time it appears likely that some of these experiments can lead to basic new insights into phenomena related to materials processing methods and, hopefully, to future commercial exploitation of new methods for production of selected products of high value. As space transportation costs are reduced with development of the space shuttle and reuseability concepts, the range of feasible materials processes will increase rapidly as products of lower dollar value per pound can be considered. It goes without saying that initial experiments should emphasize heavily the acquisition of new basic knowledge and that for some time in the future only commercial products having an extremely high monetary worth per unit weight can be considered for pilot production studies.

EXAMPLES OF WEIGHTLESS MATERIALS PROCESSES

In two symposia which NASA has held at the Marshall Space Flight Center, a large number of specific suggestions have been made for new types of processes or for improvements in existing materials preparation methods which may be applicable in the future to commercial production of uniquely valuable products of relatively modest weight. I shall not attempt to summarize these ideas for exploitation of the removal of weight forces. Hans Wuenschel and other speakers in this session are covering many of these ideas. I will restrict my attention to new processes which make use of the following categories of phenomena attending the removal of weight forces:

1. The elimination of buoyant separation of melt phases of different densities.
2. The elimination of thermal convection currents.
3. The possibility for crucibleless melting of metals and ceramics.
4. The possibility for solidification in the absence of contact with molds.
5. Shape forming with surface tension and electromagnetic field forces.

We can think of many processes which exploit these new possibilities either singly or in combination.

Elimination of Gravitational Phase Separation

Under the first category, namely the elimination of gravitational separation of melt phases of different densities, we can consider the following candidate products, which are a partial listing of ideas suggested to date:

1. Dispersions, emulsions and composite materials.
2. Alloys.
3. Foam metals.
4. Foam glasses.

Many dispersions of interest for metallurgical products involve components with widely different densities. Examples are rare earth oxide dispersions in superalloys, oxides of fissionable materials in metallic reactor fuel elements and dispersions of small particles of glass in a matrix having a different index of refraction to form phototropic materials or Christiansen filters.

Although it has been learned that cerium and lanthanum oxide dispersions in jet engine blade alloys containing chromium can greatly extend operational lifetime, these components presently require powder metallurgy techniques which result in relatively low creep resistance. Buoyant segregation of oxide particles presently prevents casting of these parts which could lead to improved properties and lower cost. The value of jet engine

components is high enough that they are conceivable candidates for future space manufacturing if space transportation costs can be reduced to the extent that has been estimated by NASA for the 1980's.

Reactor fuel elements and control rods frequently use dispersion techniques to distribute particles of fuel or nuclear poisons in metallic elements. These particles are frequently in the form of oxides. Powder metallurgy techniques are often used. The dollar value per pound of parts within a nuclear reactor core is in many cases high enough to justify even large space transportation costs if casting of these parts can lead to significant increases in core lifetime.

In some alloys phase segregation can occur to an extent that buoyant segregation is encountered. For example, it is believed that buoyant separation of manganese from lead tin telluride thermoelectric material is observed before solidification and improved material was observed by rapid cooling of extruded needles. (1) It goes without saying for this example as well as all others in which consideration is given to a removal of buoyant separation in a weightless environment, that one must be assured that segregation cannot be as well prevented by other means. Rotating clinostats can be considered for prevention of segregation where the fluid circulation due to rotation is not detrimental. Another approach, of course, would be to continually stir the solidifying melt by the use of electromagnetic eddy currents. An alternate effect of weightlessness in such processes might also be restriction of grain growth by solidification at sub-cooled temperatures, discussed later below.

A number of alloys used in electric switching applications involve phases of widely different densities. The General Electric Switchgear Department currently utilizes such materials prepared by power metallurgy techniques. Casting of such components can conceivably lead to product improvements and again we speak of products of relatively high value in circuit breakers, relays, etc.

Elimination of gravity forces during fabrication of composite materials including dispersion particles or foams has been discussed by Steurer (2).

Although foam metals containing inclusions of gases are presently made by our Metallurgical Products Department, materials of much lower density and conceivably better structure could be made by foaming in a weightless environment. Such foams might have many applications (crushable structures, battery electrodes). Similar foams can be constructed from glasses. Formation of such foams and microspheres has been discussed by Steurer (2). Examples where the weightlessness of space would make possible significant improvement over products prepared in a gravity environment would be limited to parts of reasonably large size where normal solidification rates are low enough to allow separation and sagging in the presence of gravity.

When certain oxide electronic crystals are formed from glassy melts, gravitational settling of crystals to the bottom of the crucible is often observed due to the relatively high density of the crystals. Many of these crystals discussed by Henry (3) are of extremely high value and the potential for growth of larger crystals by avoidance of crucible contact is of potential interest.

Elimination of Thermal Convection

The effect of thermal convection in forming dislocations in crystals grown from melts has been described by Utech and Grodzka (4&5). Hamalainen (6) has also described frozen Bénard convection cells in thin alkali halide crystals. This work demonstrates the importance of thermal convection upon the crystal structure obtained. The effect of thermal convection during glass formation on the homogeneity of glasses has been discussed by Deeg (7). It seems likely that in many other cases the effects of thermal convection may have as yet unrecognized effects.

Crucibleless Melting

Limited studies of the potential for crucibleless melting of metals have been performed in terrestrial experiments where small spherules of metals have been levitated and melted by use of radio frequency induction fields (8 thru 22). The objectives of this work have generally fallen under one of the following categories:

1. Melting and reaction of refractory or reactive metals some of which are contaminated by any contact with crucible.
2. Formation of an alloy completely free from segregations.
3. Observation of subcooling below normal freezing point which can be achieved routinely with some metals.

The method has not found commercial application for several reasons. First, levitation is not practicable for poor conductors. Secondly, the required levitation power is often so high as to preclude separate control of specimen temperature. In other words, a reduction in RF heating of the specimen will cause loss of levitation or pouring from the bottom of the specimen. Instabilities are sometimes encountered, and in any event the mass of material which can be prepared is severely limited. Since levitation is the most obvious property of the weightless space environment, we can for the first time consider a whole range of new processes of this type and their potential application to preparation of large quantities of material.

Removal of the requirements for levitation of a crucibleless melt means that we can have complete latitude in heating of the specimen and its temperature control during solidification. Materials can be prepared which are nonconductors, and many suggestions have been made for new glass processes which should be possible in the space environment.

Besides the possibility for reacting and melting materials without crucible contact, a corollary is the ability to provide super heating to reactive and high melting metals for which skull melting techniques must currently be used. This opens up the possibility for precision casting of these materials which cannot at present be accomplished with the negligible superheat available in skull melting.

The Possibility for Solidification in the Absence of Contact with Molds

In terrestrial levitation experiments, extreme degrees of subcooling before solidification are often observed (23). Walker has achieved subcooling for a number of materials in glass lined crucibles. In some cases the degree of subcooling is believed to approach that at which homogenous nucleation occurs. The possibility exists that some materials may form new phases if solidified in the absence of heterogeneous nucleation caused by crucible or mold contact. For example, a new phase of gallium denoted as Gallium 3 has recently been prepared in minute quantities at a temperature of -30°C centigrade (24).

The possibility for forming glasses from materials which normally crystallize through heterogeneous nucleation has been discussed in papers by Olsen and Happe (25). Since the nature of such products cannot be anticipated at present, it is clear that containerless solidification experiments must initially be proposed with emphasis upon obtaining basic information rather than with any attempt to anticipate commercial applications.

It has been suggested by Witt (26) that difficulty encountered in pulling thin filaments of single crystal material from melts in studies by Monsanto Research would be greatly relieved if it were possible to suspend a crucibleless melt of boron, for example, and apply forces to the melt which would oppose forces due to withdrawing a boron fiber at a rate allowing single crystal formation.

The possibilities for formation of near perfect spheres by solidification of melts under the sole action of their own surface tension has also been suggested.

Shape Formation Through Surface Tension and Inertial and Electromagnetic Fields

Deeg (27) has suggested possibilities of fire polished glass surfaces for spherical or spheroidal surfaces which could be formed by centrifugal action in a freely suspended rotating melt. Rotations to produce an oblate spheroidal form of given eccentricity can be easily imparted to a floating mass by means of the orthogonal coil sets discussed in a following section

Alternatively, or, in conjunction with inertial forces produced by rotation, electrostatic fields can be applied to perturb the spheroidal shape. If the electric field at the surface of a conductor is represented by E , the local curvature imparted to the surface will be given by

$$\sigma \left(\frac{1}{r_1} + \frac{1}{r_2} \right) = p + \frac{E^2}{8\pi} \quad (\kappa - 1)$$

where r_1 and r_2 are the radii of the curvature in two orthogonal directions, p is the internal pressure, σ is the surface tension, and κ is the dielectric constant. Where only slight departures from spheroidal form are required, design of suitable electrodes to furnish fields to produce a desired shape may be feasible.

POSITIONING AND HANDLING OF CONTAINERLESS MELTS - THEORETICAL AND EXPERIMENTAL STUDIES

A large number of the suggested new processes in weightless processing of metals and ceramics involve at some stage a floating molten mass out of contact with crucibles or molds. A floating mass of this type, held together solely by its own surface tension force and free to oscillate in shape, rotate and support internal fluid currents which might be driven by these or other applied forces, represents a phenomenon with which we have had little experience. Such phenomena, of course, are briefly encountered in shot tower processes and in free falling liquid streams but here the effects of air resistance and, usually, lack of time to establish equilibrium exist.

We have begun a study to investigate the physical problems associated with the melting, handling and solidification of such freely floating masses. The study of the basic physics involved in such processes leads quite naturally to a definition of the experimental facilities which will be required to handle a range of suggested processes. We have also begun the development of some new physical hardware concepts which will be required in such facilities.

Shape Oscillations

The mathematical physics of small shape oscillations in a liquid mass under the sole action of surface tension and viscous and inertial forces was treated by Lord Rayleigh (28), and more recently by Chandrasekar (29). The extension of this work to include large oscillations and large viscosity have been made by Benedikt (30) and Reid (31). For reasonably small oscillations, Figure 1 gives the oscillation frequency and time decay constant for shape oscillations in which the shape is alternately a prolate and oblate spheroid. This is the simplest mode of oscillation. More complex shape oscillations can also occur; for a given material the oscillation frequency will be greater and the decay time shorter than for the mode for which Figure 1 applies. The mathematical expressions for the frequency and decay time for a given oscillation mode are available from the classical literature (32).

Mass Limitations

Shape oscillations in free floating melts are to be expected whenever exciting forces are applied such as by means of radio or audio frequency fields used for position control. It is of course important to insure that no shape oscillation be initiated which can rupture the floating mass. The largest size mass which can be handled and kept intact thus depends upon the magnitude of position control accelerations which it is necessary to apply. These accelerations may range from $10^{-4}g$ to $10^{-7}g$ in practice as discussed below. For materials of reasonably high melting points, it appears that the upper limit to the mass which can be processed in a space facility will probably be determined by the maximum size of the available heating power source. For low melting materials, surface tension maintenance of mass integrity may enter as a limitation on mass. Simple calculations (33) indicate that masses of at least tens of kilograms can be

considered even for the least favorable requirement, (10^{-4} g control accelerations)

Rotations

For freely floating liquid masses which are put into rotation, various oblate shapes can be achieved by suitable choice of angular speed. For reasonably good conductors, these angular velocities can easily be imparted by application of rotating magnetic fields in an induction motor analogy. The rotating magnetic field would be produced by pairs of orthogonal coil sets phased in quadrature. These same coils can also be used for position and velocity control as discussed in the following. Shape oscillations will damp out within reasonable time periods as can be seen from Figure 1 and precision spheroidal shapes can be expected. Excessive angular velocities can of course lead to rupture of the liquid mass.

Electromagnetic Positioning and Sensing

In this section I will summarize theoretical and experimental work which we have done on electromagnetic position sensing and control for floating spherical objects. We have also done limited work on electrostatic and magnetostatic position control. The mathematical solutions for the electromagnetic field induced within conducting bodies under the influence of alternating applied fields has been given in the physics literature for many simple configurations. The one of main interest to us is a solution given by Smythe (34), for a conducting sphere placed into a previously uniform alternating magnetic field. In using alternating magnetic fields for position control and sensing, nonuniform fields must be used. Nevertheless, Smythe's theoretical model gives a good base approximation for the magnetic dipole moment induced in the sphere. The force can then be calculated using this approximate dipole moment and the actual gradient for the nonuniform field employed. The magnetic vector potential \vec{A} within the conducting sphere is found by solving the differential equation,

$$\nabla^2 \vec{A} = \mu \sigma \frac{\partial \vec{A}}{\partial t} \quad \begin{array}{l} \mu = \text{permeability} \\ \sigma = \text{electrical conductivity} \end{array}$$

subject to the boundary condition that the field outside the sphere approaches the applied field at distances remote from the sphere and that the field is finite everywhere. For a sinusoidally oscillating field, we will write the vector potential time dependence as $\exp(i\omega t)$ so that

$$\frac{\partial \vec{A}}{\partial t} = i\omega \vec{A}$$

The current density within the sphere is given by

$$\vec{j} = -\sigma \frac{\partial \vec{A}}{\partial t}$$

and the magnetic field \vec{B} is found from

$$\vec{B} = \text{curl } \vec{A}$$

Figure 2 shows the variation of magnetic field along the sphere radius for various sphere conductivities and field frequencies. The graph is made dimensionless as discussed in the following.

The electromagnetic field is absorbed as it passes into the sphere and the characteristic length for this absorption (known as the "skin depth" δ) is given in terms of the sphere permeability μ , electrical conductivity σ and the angular frequency of the applied field ω by the equation

$$\delta = (\mu \sigma \omega)^{-1/2}$$

The variation of magnetic field strength, electric current density and consequent forces and heating rates depend only upon the skin depth and the applied external field strength. Thus it is appropriate to plot results in terms of ratios of sphere radius to skin depth. This ratio ranges from 0.1 to 5 in the figure. This covers, for example, a 1 centimeter aluminum sphere at 10 kilocycles at the high extreme and molten glass of 1 cm radius at 10 megacycles at the other extreme.

The total force on the sphere can be computed in terms of the dipole moment from the eddy current distribution. However, since the body forces acting on the fluid within the sphere will generate internal fluid currents, we wish also to study the details of distribution of these forces within the sphere. Figure 3 shows the variation of radial body forces for various positions within a sphere over a range of ratios of skin depths to sphere radii. For good conductivity and high frequency, the force is concentrated near the surface of the sphere. These forces will give rise to circulating fluid currents within the sphere. If the sphere is immersed in a uniform oscillating magnetic field or one which varies only slowly with position, as would be created by a single pair of coils as shown in Figure 4, fluid currents will be excited which travel radially inward at the sphere equator and outwards to the poles defined by the coil axis.

For complete position control, three orthogonal sets of coils will be used which gives rise to a number of choices of modes of coil excitation. One scheme we have considered consists of an equal duty cycling of the three coil sets so that only one is excited at a given time for position sensing and control. If, on the other hand, three coil sets are excited simultaneously, more complicated current distributions within the sphere can be obtained as illustrated in the right hand portion of Figure 4.

These fluid currents generated by magnetostrictive forces may be very useful for stirring of floating melts just as this type of stirring has proven very useful in terrestrial experiments to obtain well homogenized alloys and dispersions. This is one possible answer to the question of how to stir melts without introducing heterogeneous nucleation from the introduction of stirring rods, etc.

For electromagnetic fields having a significant gradient, such as can be obtained by differential excitation of a given coil pair, translational forces will be imparted to the sphere. For the case where only one member of a pair is excited, Figure 5 shows the manner in which acceleration of an aluminum sphere would vary with sphere position for a coil excitation of one ampere turn. We have experimentally verified these curves in the low force region which will be useful in the weightless space environment. Figure 6 gives experimental force measurements which we have made down to a level of five dynes on a sphere weighing 1.3×10^{-4} dynes, and a corresponding acceleration of $3.6 \times 10^{-4}g$. These measurements have been made by means of coils with horizontal axes and a one centimeter radius sphere suspended on a pendulum of length up to two meters. We have also made limited measurements for precision spheres free to roll on a precision glass tilt table and are currently developing other methods capable of measuring accelerations down to $10^{-6}g$. We have operated torsion balances in other experiments with sensitivities as low as 10^{-5} dynes, but have not as yet utilized this device in our electromagnetic positioning experiments.

Laboratory Demonstration of Two-Axis Electromagnetic Sensing and Positioning Servo

We have prepared a film showing current activities in developing demonstration hardware based on the principles which I have described. The first scenes from the film (see Figures 7 and 8) show a general view of the laboratory setup and the two axis coil system for controlling the ball position laterally. A solid sphere of approximate 1 in. diameter is suspended from a long pendulum so that observable lateral translations occur when forces are applied capable of causing accelerations in the milligravity region. The next scenes from the film show that the ball is confined to stay within the potential well created by the four coils even in the absence of position and velocity detection and position control servo action. The coils are excited to a degree where the gravitational restoring forces due to the pendulum suspension are small compared to the electromagnetic position restoring forces. The shape of the potential well created between the coils depends upon the phasing of the alternating current to the various coils. The wells generally have a pincushion cross section and can be made to have a very low slope in the central region when opposite members of a coil pair are connected in phase. With the position sensing and position control servo actuated we see that the ball is not only confined within the potential well of the coils but is rapidly brought to the center of the well and its velocity relative to the coils brought to zero. Elimination of any velocity error relative to the space laboratory facility is important for those processes where it is desirable to completely eliminate position control forces during part of the process, such as for example solidification of melts into an accurate spherical or spheroidal shape.

The next scene shows control of position of the sphere by trimming the steady state excitation in the coil pairs. Here the trimming was carried out rather slowly to avoid initiation of position oscillations.

The next scene shows the manner in which the suspended sphere can be spun up by phasing the excitation of orthogonal coil pairs in quadrature. Here the sphere is copper and is supported by a

ball bearing. Because of the bearing friction a large slip is encountered between the rotating field and ball. In the zero gravity environment, near perfect synchronization would be expected and field rotations of several cycles per second will give significant deformations into oblate spheroidal configurations for sizes in the range of one to several centimeter radius.

The next scene shows initial tests of an electrostatic positioning device. Here the sphere is surrounded by several pointed electrodes. Field strengths of several thousand of volts per centimeter were used with a water filled thin glass spherical shell of approximate 1 in. diameter. We can note that, even at the low temperatures involved here, corona discharge ultimately builds up a charge on the suspended sphere leading to erratic behavior. It should be noted, however, that in the zero gravity environment, much lower field strengths, on the order of volts per centimeter, can be contemplated.

GENERAL REQUIREMENTS FOR SPACE EXPERIMENT FACILITIES

Each of the proposals for exploiting the weightless feature of the space environment in metallurgic and ceramic processing of course requires an individual study of facility requirements in terms of heating power, instrumentation, size of facility, etc. Since a large number of these suggestions involve the handling of a floating molten mass out of contact with crucibles or molds it is nevertheless possible to define, even at this stage, facilities which will be capable of accepting a large number of candidate new weightless processing experiments. We have begun a study for NASA to define the physical requirements for a wide range of potential new crucibleless melting and solidification experiments in order to define limits to the range of variables which can be handled in one or more facilities which may be practicable for early incorporation in the post Apollo program.

Some of the physical variables which are important in defining the required experimental facilities are summarized below:

<u>Process Variable</u>	<u>Facility Requirement</u>
Melting temperature	Heating power
Size of batch	
Heating rate	
Requirements for vacuum or controlled atmosphere	Processing chamber and accessories, starting material, handling devices
Requirements for pre-melting of pre-cast specimens or for crucibleless mixing and reaction	

Cooling rate	} Position control, free floating volume
Solidification temperature	
Processing time	
Purity requirements	
Requirements for absence of contact with crucible of melt during some part of the process	} Electromagnetic or electrostatic fields, provision for rotation of melt
Requirements for stirring	
Requirements for shaping or molding	
Likelihood and nature of included bubbles	
	Requirements for stirring and bubble detection/elimination technique

I should like to give a few examples of work we are doing to translate some of these rather general process requirements into a definition of the facilities required to handle a wide range of processes. The requirements on facilities imposed by position control, position sensing, heating, processing time, free floating volume required for the specimen, maximum permissible accelerations in terms of shape distortions, etc. are of course all related. We first discuss these requirements separately; however, in the course of a detailed discussion the interdependence of these requirements will become obvious and the region of intersection of the various experiment requirements in terms of facilities will, in most cases, define the required facilities within fairly specific limits.

Positioning Requirements for Crucibleless Melting Experiments

Type of Positioning Control

We have concentrated upon the study of positioning by means of applied electromagnetic fields. This includes not only electromagnetic fields which are driven at audio or radio frequencies but electrostatic and magnetostatic fields as well. For good conductors, position control by means of interaction between applied alternating fields and the eddy currents induced within the processed specimen is particularly convenient. Induced eddy currents can also be used to heat the specimen and control its temperature. In this section we shall discuss the range of frequencies and powers required for position control of free floating molten or solid masses.

For good conductors, eddy current position control at audio frequencies can be achieved without appreciable heating of the sample. If simultaneous eddy current heating is desired, higher frequencies can be used and the power used for heating is more than ample for position control of the specimen. For this type of process, position control is achieved by small differential excitations in coils on opposite sides of the specimen where the total eddy current power dispersion in the specimen can be held constant. Other types of processes can be considered where other means of heating are used.

Figure 9 shows the eddy current power absorbed by a free

floating specimen when it is accelerated by an eddy current positioning device at a rate $10^6 g$ ($10^{-3} \text{ cm sec}^{-2}$). This acceleration is characteristic of the lower limit which may be achievable in low altitude earth orbiting facilities unless compensation for deceleration due to air drag and gravity gradients is provided. The power requirement depends upon the sphere mass, density, electrical conductivity and driving frequency. It also depends upon the magnetic permeability of the specimen but our main interest is in molten materials whose temperatures will be above the Curie temperatures so that we may assume unit permeability. It would be possible to plot this figure with a dimensionless abscissa which is the ratio between the sphere radius and the skin depth to which the electromagnetic field penetrates. For facility definition it is preferable however to exhibit engineering parameters such as frequency, power and sphere size for specific processes. We see from Figure 9 that the minimum power required for positioning is linearly proportional to the sphere radius and depends drastically upon the conductivity of the material. For example, minimum position control power for a one centimeter aluminum or molten glass sphere at an acceleration of $10^6 g$ ranges from 10^{-5} watts to 100 watts. For molten glass of relatively high conductivity the corresponding power required for position control drops to 10 milli-watts. The corresponding frequencies required for position control range from the low audio range for metals to hundreds of megahertz for molten glass of poorest conductivity.

For relatively small experiment vehicle carriers, such as the proposed dry work shop, astronaut body motions may occasionally impart accelerations to the vehicle approaching $10^4 g$ for short time periods. For most processes, sufficient free volume can be provided surrounding the specimen being processed so that it can remain free floating without seeing accelerations of this magnitude. Since these accelerations will average out to zero over a time period on the order of a minute or less, it is highly likely that rigid process control with respect to the vehicle will not be required. At least for short processing times, the operation of such accelerating forces could easily be inhibited until process completion. If it is desired to provide rigid positioning of free floating objects with respect to the vehicle during accelerations as high as $10^4 g$, we can refer to Figure 10 for the required positioning powers. For the metals in the range up to ten centimeter radius the positioning powers are essentially negligible (less than one watt). For high conductivity molten glass the power requirement ranges up to only ten watts. For poorly conducting molten glass, required positioning powers can reach the multi kilowatt region and hence it appears that eddy current position control is not a likely candidate in this extreme case.

For material conductivities, sphere radii, and driving frequencies such that the skin depth of penetration exceeds the sphere radius, a change in driving frequency will cause the acceleration and power dissipated to vary in the same proportion. Thus increasing the frequency so as to double the acceleration will also double the power dissipation. Curves showing the manner in which the acceleration and power dissipation vary with frequency have been prepared by Fromm and Jehn (35). These curves show that for frequencies and conductivities such that the skin depth is a small fraction of the sphere radius the power dissipation increases with frequency more rapidly than acceleration. For the metals, positioning with negligible heating at low

frequency is relatively simple. For a very poor conductor such as molten glass, an increase in frequency to at least the high audio range and even into the tens of megahertz range is required and hence eddy current heating cannot be avoided. We have displayed the dependence of power dissipation, normalized per unit sphere surface area, and acceleration as a function of driving frequency for metals in Figures 11 and 12.

Here we see that the choice of frequency for a positioning facility can be made conveniently in the audio region if the specimen is heated by some means other than eddy currents. In practice, we can select a frequency somewhat arbitrarily, such as ten kilohertz, for which requirements for electronic circuit design are extremely simple. The actual positioning forces obtained at a given driving field strength will then of course depend upon the resistivity and size of the material sphere being processed. In the servo positioning device which we are developing, the exact restoring force per unit position error is not particularly critical. Moreover, the servo loop gain can be varied quite easily, if desired, for different specimens by turning a knob to a precalculated position. In practice, such an adjustment would probably not be made unless the material resistivity varied extremely from one specimen to the next.

As a matter of interest, and since it plays the fundamental role in determining both the positioning forces and power dissipation, we show the skin depth as a function of frequency in Figure 13. Depending upon the frequency and conductivity we see that the skin depth can range over 7 decades of variation, thus the ratio of skin depth to sphere radius can vary from values much less than unity to values much greater than unity for cases which will be of interest. This is in contrast to work in terrestrial levitation experiments where skin depths greater than the sphere radius are of little interest since they in general do not provide sufficient positioning force to levitate the material in the one g environment. The greater freedom of choice of frequency and skin depth for the case of materials which are processed in the zero gravity environment allows for eddy current heating which can be adjusted independently from the requirement for positioning.

An alternative way for position control of a freely floating molten or solid mass is the use of electrostatic fields. An electrostatic field introduced into the space around a floating object will induce an electric dipole moment in the specimen. This induced electric dipole moment will then interact with any gradient or nonuniformity in the applied field to produce a translational force. If we denote the position coordinates as x_1, x_2, x_3 and the electric field components as E_1, E_2, E_3 , the components of the force are given by

$$F_\mu = \frac{\partial}{\partial x_\nu} \left(\frac{1}{2} \epsilon E_\nu^2 \right) \quad \text{sum over } \nu = 1, 2, 3$$

$$k = \text{constant involving the dielectric constant}$$

The introduction of a dielectric or metal specimen into the space will perturb the field from its previous value. The corresponding induced electric dipole moment for spheres and many other shapes of interest has been derived in some of the classical literature on electric potential theory. For example, the dipole moment induced in a pyrex glass sphere of one centimeter radius

by a field of one KV cm^{-1} will give rise to an acceleration of $2 \times 10^{-4} g$ if the field strength changes by 30% over a one cm interval. Such a gradient can easily be provided from, for example, six electrodes surrounding the suspended specimen in opposing pairs along each of three rectangular axes. For accelerations of $10^{-6} g$, field strengths of only tens of volts per centimeter will be required. Although electrostatic field position control is in principle no more complex than eddy current positioning such as we have discussed, it has some inherent problems if used in conjunction with materials which outgas. At high field strengths, corona discharge may be encountered. For the case of specimens which outgas metal vapors, plating and consequent shorting of insulators and electrodes may be encountered unless adequate baffle systems can be provided. It appears that, at least for glasses, these problems can probably be solved and that in this sense there is an overlap in the region of applicability of electromagnetic and electrostatic positioning.

Position Sensing

A number of position sensing schemes are available which can be used for position control or handling of free floating solid or liquid materials. Besides the eddy current position sensor which we have developed and applied to sensing of metallic objects, one may also consider bolometers or other heat sensing detectors or changes in electrostatic capacitance. The latter would be a natural solution in the case of an electrostatic position control device.

Another possibility is optical sensing, either by emitted radiation from a hot object, by interception of optical light beams, or visual or photographic observations. It is expected that visual observations of specimens during processing should be provided wherever possible, particularly in pilot experiments.

Any of the above position sensing methods, except photographic, can be used to actuate a position control servo in the same manner as is done in our demonstration electromagnetic device. It is quite likely that none of the above methods will be applicable to all processes but that each will have its own domain. It appears that these domains overlap. For many processes, either the eddy current position sensor or the bolometer position sensor will be adequate. For samples of very high resistivity which must be positioned at temperatures too low for detection of emitted radiation, the electrostatic or optical methods can be considered. Normally, however, positioning of these specimens can perhaps be performed mechanically when they are removed from the processing chamber after cooling.

Heating and Temperature Control

The minimum heating power which must be provided is that necessary to furnish surface radiation loss from the specimen. If a controlled atmosphere is utilized, additional power will be conducted away by the gas. In this connection it must be noted, however, that normal convection due to buoyancy of the heated gas will be absent and that under these conditions, the gas will act as a good insulator. For many materials, including most metals, the choice of heating methods can be made independently of the choice for position control. For materials of very high resistivity such as glasses, the electromagnetic positioning

can give rise to eddy current heating dissipations which can become significant so that it may be advantageous to consider RF heating, at least for things such as molten glass having reasonably good conductivity. One might be led to think, conversely, that the choice of eddy current or RF heating will lead to unavoidable positioning forces. However, if RF heating is provided by pairs of coils symmetrically disposed on either side of the specimen, no net translational force will be applied to the specimen when the coils are equally excited. With such an arrangement if it is desired to impart a position control force, small differential excitations can be introduced into the coil excitations through a servo loop actuated by position or velocity errors in such a way that the total power dissipation in the specimen is unchanged. The specimen temperature can be controlled by raising or lowering the total coil excitation power.

Figure 14 simply illustrates the surface radiation loss, or minimum heating power required to achieve the melting or transition temperature for several materials of interest. By way of illustrating the relation between the heating power requirement, if this is provided by eddy currents, and the eddy current positioning requirements discussed earlier, we may consider the example of lead telluride at its melting point. This requires a minimum power dissipation in a one centimeter radius sphere of 50 watts. Referring back to Figure 11 we see that this requires a driving frequency of 300 kilohertz at 300 ampere turns, corresponding to a maximum acceleration of .04 g if all of the power is furnished by a single coil. Any lower value of position control acceleration can be provided by shaping the driving power between two coils, one on either side of the specimen.

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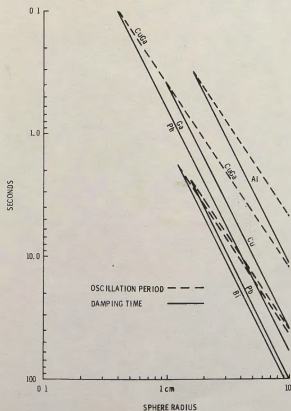


Figure 1 Shape Oscillation Periods Free Floating Melt

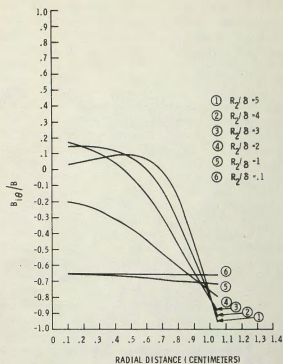


Figure 2. θ Component of Magnetic Field per Unit Magnetic Induction in Aluminum Sphere of Radius $R_2 = 0.4125$ Inch at Colatitude $\theta = 45^\circ$ Showing Penetration of Field into Spheres as a Function of Skin Depth

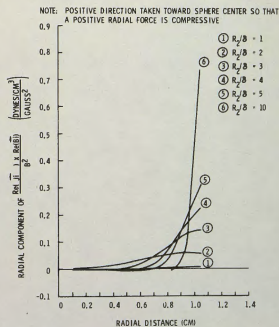


Figure 3. Radial Component Force/Volume per Unit Magnetic Induction Squared for Aluminum Sphere $R_2 = 0.4125$ Inch at $\theta = 45^\circ$ as a Function of Skin Depth

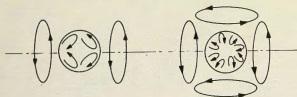


Figure 4. Fluid Currents Excited by Magnetostriction

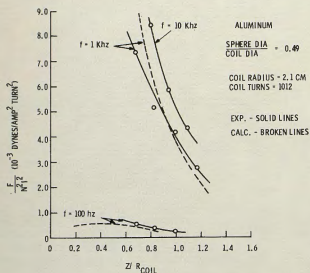


Figure 5. Force as a Function of Position

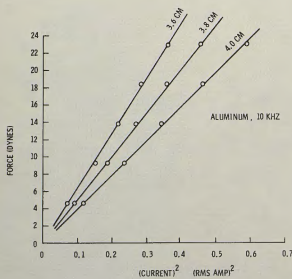


Figure 6. Experimental Force Measurements

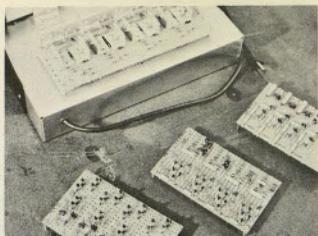


Figure 7. Position Sensing and Control Electronics

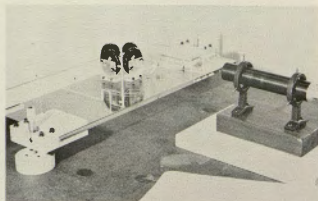


Figure 8. Positioning Coils, Pendulum Suspension and Instrumentation

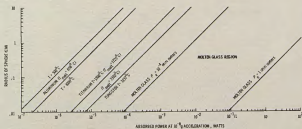


Figure 9. Minimum Power Absorbed with $10^{-6}g$ Acceleration Applied to a Sphere

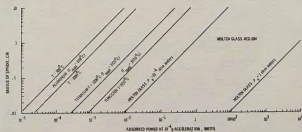


Figure 10. Minimum Power Absorbed with $10^{-4}g$ Acceleration Applied to a Sphere

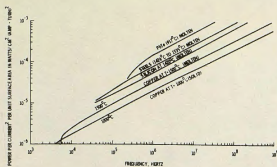


Figure 11. Power Absorbed by a Sphere Radius 1 cm (1 amp turn coil of radius 1.905 cm)

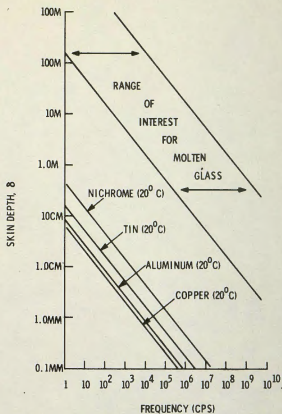


Figure 13. Skin Depth vs. Frequency for Several Common Metals and Molten Glass

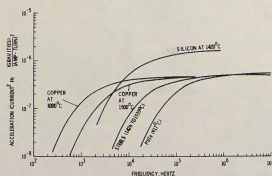


Figure 12. Acceleration/Current² Imparted to a Sphere of Radius 1 cm (1 amp turn coil of radius 1.905 cm)

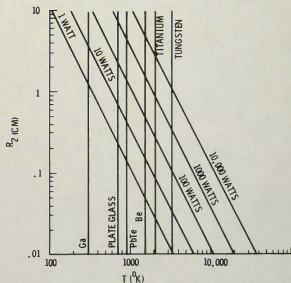


Figure 14. Surface Radiation Loss for Unit Emissivity

